

LABORATOIRE EUROPEEN POUR LA PHYSIQUE DES PARTICULES (CERN)

CERN-EP/99-124

8 September 1999

A direct measurement of $|V_{cs}|$ in hadronic W decays using a charm tag

ALEPH Collaboration ¹

Abstract

The inclusive charm production rate in W decays is measured from a study of the properties of final state particles. The sample of W pairs is selected from 67.7 pb^{-1} collected by ALEPH in 1996 and 1997 at centre-of-mass energies near 172 and 183 GeV in the channels $W^+W^- \rightarrow 4q$ and $W^+W^- \rightarrow \ell\nu q\bar{q}$. The branching fraction of hadronic W decays to a final state containing a c quark, $R_c^W = \Gamma(W \rightarrow cX)/\Gamma(W \rightarrow \text{hadrons})$, is measured to be $0.51 \pm 0.05_{\text{stat}} \pm 0.03_{\text{syst}}$. This allows a direct determination of the CKM matrix element $|V_{cs}| = 1.00 \pm 0.11_{\text{stat}} \pm 0.07_{\text{syst}}$.

(Submitted to Physics Letters B)

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⁶Supported by the Commission of the European Communities, contract ERBFMBICT982894.

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⁸Supported by the National Science Foundation of China.

⁹Supported by the Danish Natural Science Research Council.

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1 Introduction

The data collected by ALEPH in the years 1996 and 1997, at average centre-of-mass energies of 172 GeV and 183 GeV, respectively, are used to study the properties of hadronic W boson decays. The total luminosity collected in the two periods is 67.7 pb^{-1} of which 57.0 pb^{-1} was collected at the higher energy. The identification of charm jets in these decays leads to a direct measurement of the fraction $R_c^W = \Gamma(W \rightarrow cX)/\Gamma(W \rightarrow \text{hadrons})$, where X stands for \bar{d} , \bar{s} or \bar{b} . Unless explicitly stated, the charge-conjugate modes are always implied throughout this paper. Within the Standard Model, this branching ratio can be expressed as a function of the different Cabibbo-Kobayashi-Maskawa (CKM) matrix elements through the following relation:

$$R_c^W = \frac{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 + |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2}. \quad (1)$$

Assuming the unitarity of the CKM matrix, R_c^W is expected to be equal to 0.5. Therefore, a measurement of R_c^W is a direct test of this assumption. Furthermore, equation (1) can be used to extract a value of the least well known CKM matrix element $|V_{cs}|$ which is currently measured to be 1.01 ± 0.18 using $D \rightarrow K\ell\nu_\ell$ decays [1].

A charm jet tagger (called NN_c in the following) was developed to identify $W \rightarrow cX$ decays. This is based on a neural network with 12 variables as input and uses mainly information from charm lifetime, jet-shape properties, reconstruction of D mesons and lepton identification. The procedure of extracting R_c^W and $|V_{cs}|$ from the NN_c output is described in this paper. Another analysis based on a Fisher Discriminant technique is also presented as a crosscheck of the method.

2 The ALEPH detector

The ALEPH detector [2] and its performance [3] are described in detail elsewhere. Only a brief account of the parts of the apparatus relevant for this analysis is given here. Charged particles are detected over the range $|\cos\theta| < 0.95$ by an inner drift chamber and a large time projection chamber (TPC), complemented by a silicon strip vertex detector (VDET) made of two layers each providing measurements in the $r\phi$ and rz coordinates, with a resolution of $12 \text{ }\mu\text{m}$ in $r\phi$ and $12 \text{ }\mu\text{m}$ in rz , for tracks at normal incidence. The three tracking detectors are immersed in a magnetic field of 1.5 T and together provide a transverse momentum resolution of $\delta(p_T)/p_T = 6 \times 10^{-4} p_T \oplus 0.005$ (p_T in GeV/c) for high momentum charged particles.

The impact parameter of the tracks of charged particles with momentum in excess of 10 GeV/c and reconstructed with two VDET coordinates is measured by the tracking system with a precision of $35 \text{ }\mu\text{m}$ with respect to an event-by-event interaction point. This resolution allows c jets produced in $W \rightarrow cX$ decays to be selected by exploiting the longer lifetime of c hadrons with respect to other hadrons, using an algorithm based upon the track impact parameter measurement described in [4].

In addition to its rôle as a tracking device, the TPC is employed to separate charged particle species using up to 338 measurements of their specific ionization, dE/dx . This allows electrons to be separated from pions by more than three standard deviations up to a momentum of 8 GeV/c.

The electromagnetic calorimeter which surrounds the tracking detectors inside the superconducting solenoid is used, together with the TPC, to identify electrons and photons from the characteristic longitudinal and transverse profiles of their associated showers [3]. It consists of 45 layers of lead interleaved with proportional wire chambers, and covers the angular region $|\cos\theta| < 0.98$. The relative energy resolution achieved for isolated electromagnetic showers is $0.18/\sqrt{E} + 0.009$ (E in GeV).

Muons are identified by their penetration pattern in the hadron calorimeter, composed of the iron of the magnet return yoke interleaved with 23 layers of streamer tubes, and by two muon chambers, each made of two layers of streamer tubes surrounding the calorimeter.

The total visible energy is measured with the energy-flow reconstruction algorithm described in [3]. This algorithm provides a list of charged and neutral reconstructed objects, called *energy-flow particles*, from which jets are reconstructed.

3 Monte Carlo samples

The value of R_c^W is extracted by comparing the NN_c output distribution in the data to the corresponding Monte Carlo distribution, where generated events are processed through a full simulation of the ALEPH detector response and through the same reconstruction chain. The KORALW [5] event generator with the complete set of WW-like four-fermion diagrams was used to produce two samples of 200,000 WW events at centre-of-mass energies of 172 GeV and 183 GeV, generated with reference W masses M_W^{ref} of 80.25 GeV/ c^2 and 80.35 GeV/ c^2 , respectively. Additional samples with W mass equal to $M_W^{\text{ref}} \pm 0.25$ GeV/ c^2 were used for checking purposes. Gluon radiation and the hadronisation process were simulated with the JETSET [6] package while the HERWIG [7] package was used for systematic studies. The decay properties of the D^+ , D^0 , and D_s^+ mesons and of the Λ_c^+ baryons were modified inside JETSET to reproduce those given by the MARKIII Collaboration [8] and the Particle Data Group [1]. This includes the exclusive branching ratios, the inclusive production rates of π^0 , K^0 , \bar{K}^0 , K^\pm , p , and Λ and the topological branching ratios. The $c \rightarrow \ell$ spectrum was also corrected by reweighting the energy spectrum given by JETSET in the centre-of-mass system of the decaying c hadron so that it reproduces the combined DELCO [9] and MARKIII [10] data.

PYTHIA [6] was used to generate the background processes $e^+e^- \rightarrow q\bar{q}(\gamma)$, ZZ , Zee and $W\nu_e$, with integrated luminosities corresponding to at least 50 times that of the data. Events with a flavour content that could originate from WW production were removed from the ZZ sample to avoid double counting with the KORALW sample.

4 Event selection and charm tag

4.1 Event selection

The event selection was performed separately for the purely hadronic events, $W^+W^- \rightarrow 4q$, and for the semileptonic events, $W^+W^- \rightarrow \ell\nu q\bar{q}$ ($\ell = e, \mu$).

For the semileptonic events $W^+W^- \rightarrow e\nu q\bar{q}$ and $W^+W^- \rightarrow \mu\nu q\bar{q}$, the neural network described in Ref. [11] is used for the selection. The signal efficiency is about 90% for a purity of 95%. The selected events are then forced into two jets using the DURHAM-P [12]

algorithm, the lepton being removed when doing the clusterisation. Events corresponding to $W^+W^- \rightarrow \tau\nu q\bar{q}$ decays which pass this leptonic selection are treated as signal events in the fit procedure.

In the fully hadronic channel, a neural network package is again used to select the events. A description of this selection algorithm and the variables it uses, as well as the distribution of the neural network output, is given in [13]. This gives a signal efficiency of 83% for a purity of 86%. The selected events are forced into four jets using DURHAM-P, and the pairing of the jets is done by minimizing the quantity $(M_{ij} - M_W^{\text{ref}})^2 + (M_{kl} - M_W^{\text{ref}})^2$, where the subscripts i, j, k, l refer to the four jets.

The expected number of events in the different channels are listed in Table 1 for the two years of data taking. It has been checked that the selection efficiencies are the same for hadronic W decays with and without a charm quark and therefore the event selection does not bias the fraction of charm jets in W decays.

Table 1: Expected number of events for the semileptonic and hadronic WW decays and for the main background sources. The expected number of events are given for the integrated luminosity of 10.65 pb^{-1} and 57.01 pb^{-1} obtained at centre-of-mass energies of 172 and 183 GeV, respectively.

Selection	4q	$\ell\nu_\ell qq$	$\tau\nu_\tau qq$	$q\bar{q}(\gamma)$	ZZ	Zee	MC	data
Semileptonic 172	0.	30.6	1.0	0.4	0.1	0.2	32.3	31
Hadronic 172	45.4	0.2	0.1	6.3	0.8	0.	52.8	54
Semileptonic 183	0.1	245.	7.6	8.	1.	5.	266.7	261
Hadronic 183	322.	0.5	0.6	46.	2.	0.1	371.2	400

4.2 Charm jet tagging

The discrimination of c jets (signal) and uds jets (background) produced in hadronic W decays is based on the following properties:

1. The lifetime of c hadrons is of the order of 1 ps; therefore, their decay products have on average large impact parameters.
2. D and D* mesons produced in the hadronization process can be reconstructed through their decay products.
3. The semileptonic branching ratio for c hadrons is about 10% [14], leading to a high rate of high energy leptons in the jets.
4. As the c quark is heavier than uds quarks and is weakly decaying, the jet-shape properties will be different. In particular the multiplicity of the decay products will be larger for D mesons. Furthermore these decay products will have specific momentum p and transverse momentum p_\perp distributions (with respect to the jet axis).

From the above properties, twelve discriminating variables V_i were built for each jet. In the following, the numbers in parentheses give the weights of each variable in the neural network, as defined in Ref. [15].

The variables exploiting the lifetime of charmed hadrons are

- V_1 (0.12): the logarithm of the lifetime probability of a jet to be a uds-jet [4].
- V_2 (0.07): the equivalent of V_1 but calculated only for charged tracks with $\eta_{\text{jet}} > 4.9$ [15], where η_{jet} is the pseudorapidity of the track with respect to its jet axis.
- V_3 (0.08): a lifetime variable defined as the difference between the χ^2 when all charged tracks of the jet are assigned to the primary vertex, and the sum of the primary and secondary vertex χ^2 values when some tracks are transferred from the primary to a secondary vertex candidate [16].

The decay properties of charmed mesons are used in

- V_4 (0.06): the energy of the most energetic fully reconstructed D meson in the jet normalized to the beam energy. The D mesons are reconstructed in the following channels: $D^0 \rightarrow K^- \pi^+$, $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ and $D^+ \rightarrow K^- \pi^+ \pi^+$ [17].
- V_5 (0.06): the p_\perp^2 of the π_{soft} candidate in D^* decays, defined as the charged track in the jet with an energy between 1 and 4 GeV, having the smallest p_\perp with respect to the jet axis [18].

The leptons produced in semileptonic decays of charmed hadrons are considered in

- V_6 (0.07): the number of leptons (electrons or muons) in the jet with $p \geq 2.5 \text{ GeV}/c$. The criteria used to define leptons are those used for b physics studies at LEP1 [19].

Finally the larger mass of the charm quark with respect to u, d and s quarks is taken into account by

- V_7 (0.05): the energy of the nucleated system around the leading track of the jet, built with an invariant mass cut at $2.1 \text{ GeV}/c^2$ [20].
- V_8 (0.15): the sum of the pseudorapidities, calculated with respect to the jet axis, of the tracks within 40° of the jet axis.
- V_9 (0.09): the track multiplicity in a 40° cone around the jet-axis.
- V_{10} (0.10): the momentum of the leading track in the jet.
- V_{11} (0.04): the sphericity calculated with the four most energetic tracks of the jet [21].
- V_{12} (0.11): the sum of the energies of the four most energetic tracks of the jet.

These jet variables are then used as input of a feed forward neural network with one hidden layer of 10 neurons, and an output layer consisting of one output node giving the variable NN_c used to discriminate between c jets from W decays (output close to +1) and uds jets (output close to -1). The neural network was trained separately at 172 GeV and 183 GeV, and for semileptonic and 4q WW events. The distribution of some of these jet variables can be seen in Fig. 1 for the 183 GeV data. Figure 2 shows a comparison between data and Monte Carlo for the four input variables presented in Fig. 1. The shapes

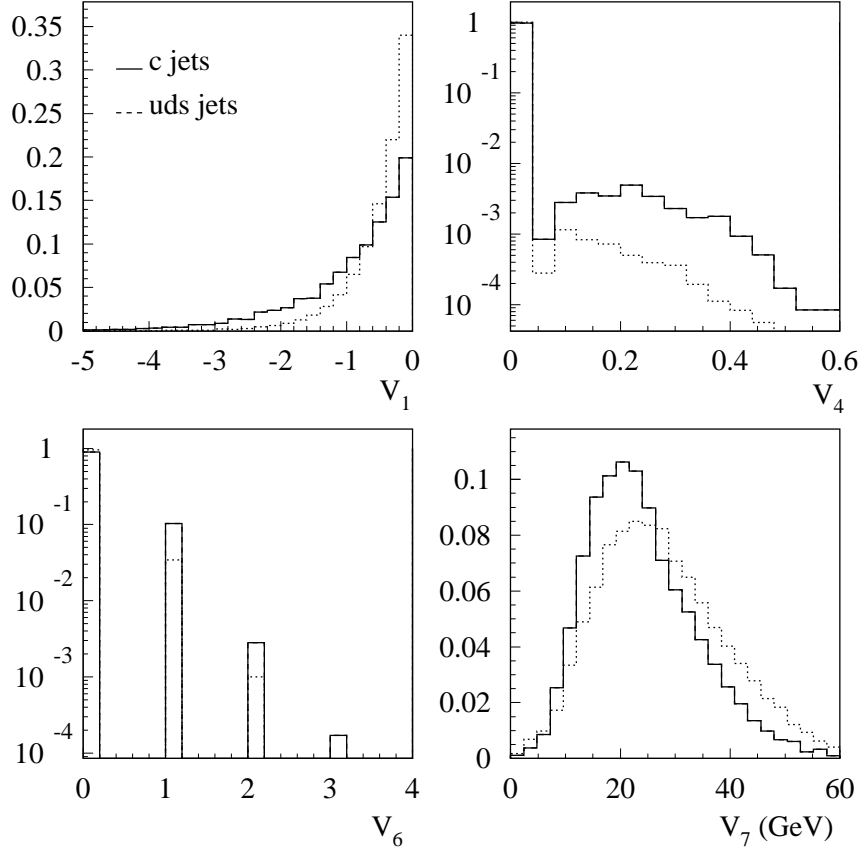


Figure 1: Distributions of four jet variables (among the twelve) used as input for NN_c for c jets from W decays (signal) and uds jets from W decays (background) at 183 GeV. The two Monte Carlo contributions are normalized to the same number of entries. Similar distributions are obtained at 172 GeV. The contributions of $W^+W^- \rightarrow \ell\nu q\bar{q}$ and $W^+W^- \rightarrow 4q$ candidate events are added.

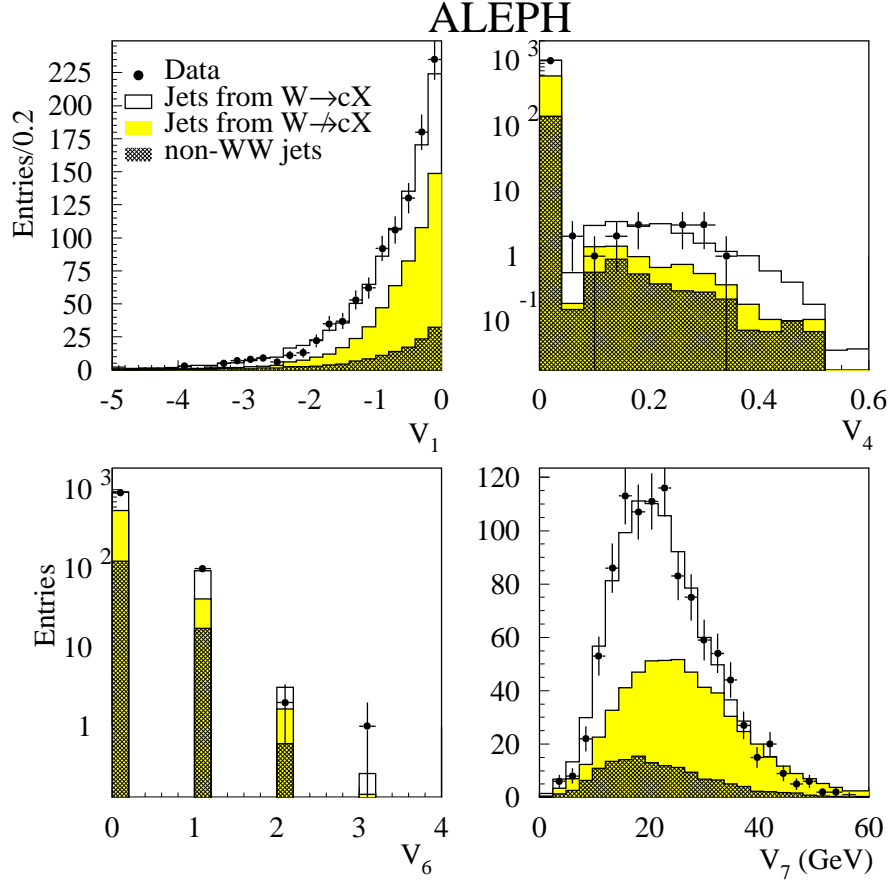


Figure 2: Distribution of four jet variables among the twelve used as input to NN_c . Comparison between data and Monte Carlo at 183 GeV for the most charm-like jet in the pair according to each variable. The contributions of $W^+W^- \rightarrow \ell\nu q\bar{q}$ and $W^+W^- \rightarrow 4q$ candidate events are added.

of the input variables and the performance of the neural network are very similar for the 172 GeV data.

The value of NN_c is calculated for each of the jets of a pair, and the jet associated to the highest value, NN_c^{\max} , is chosen as the charm jet candidate and used in the analysis to determine R_c^W . The output distributions of NN_c^{\max} obtained for $W^+W^- \rightarrow \ell\nu q\bar{q}$ and $W^+W^- \rightarrow 4q$ events are shown in Fig. 3. The shapes of the two distributions are different because of possible overlapping of the jets in the $W^+W^- \rightarrow 4q$ channel. Figure 4 compares

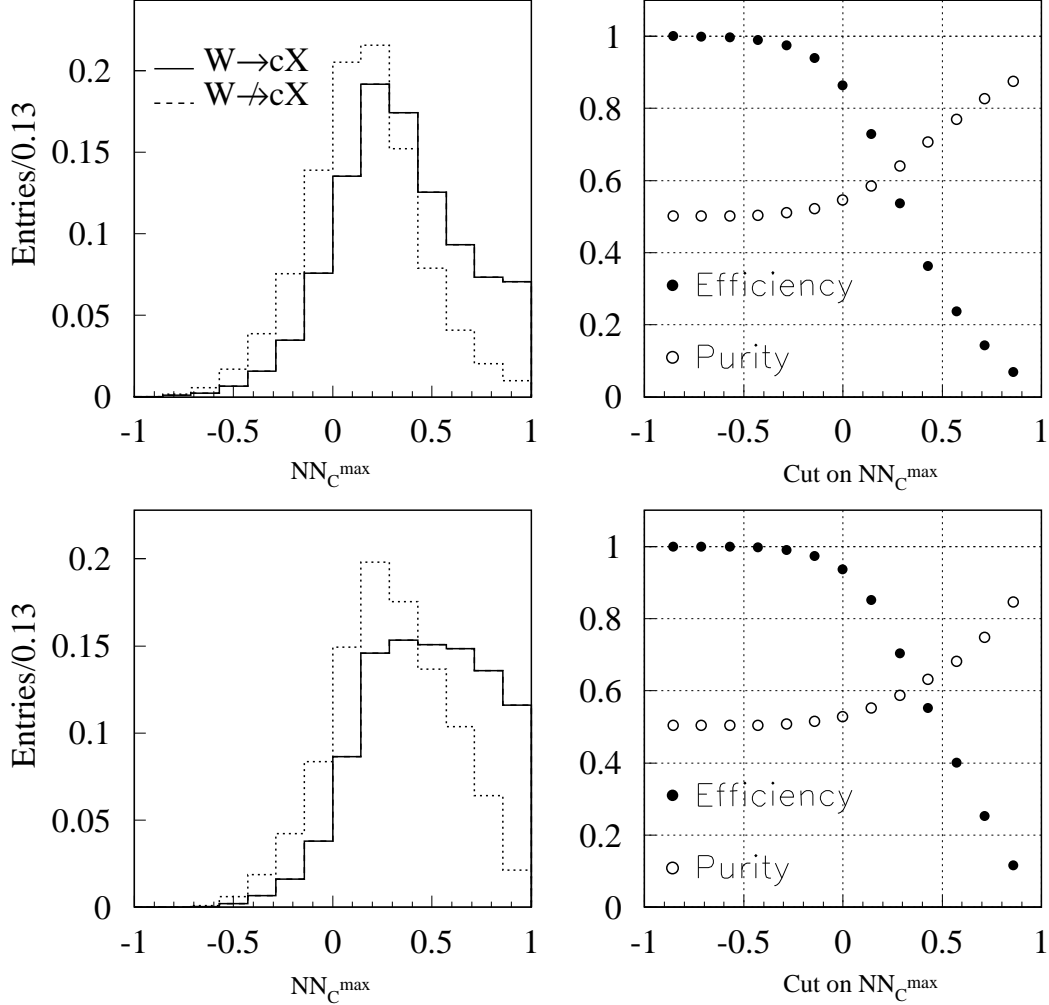


Figure 3: Monte Carlo output of NN_c^{\max} and its performance for the $W^+W^- \rightarrow \ell\nu q\bar{q}$ channel (upper plots) and the $W^+W^- \rightarrow 4q$ channel (lower plots). The purities are calculated using $R_c^W = 0.5$.

the distributions of NN_c^{\max} for data and Monte Carlo events. As there is one $W \rightarrow q\bar{q}'$ decay in semileptonic WW events, this channel contributes for one entry in Fig. 4. The two $W \rightarrow q\bar{q}'$ decays of a fully hadronic WW event contribute for two entries.

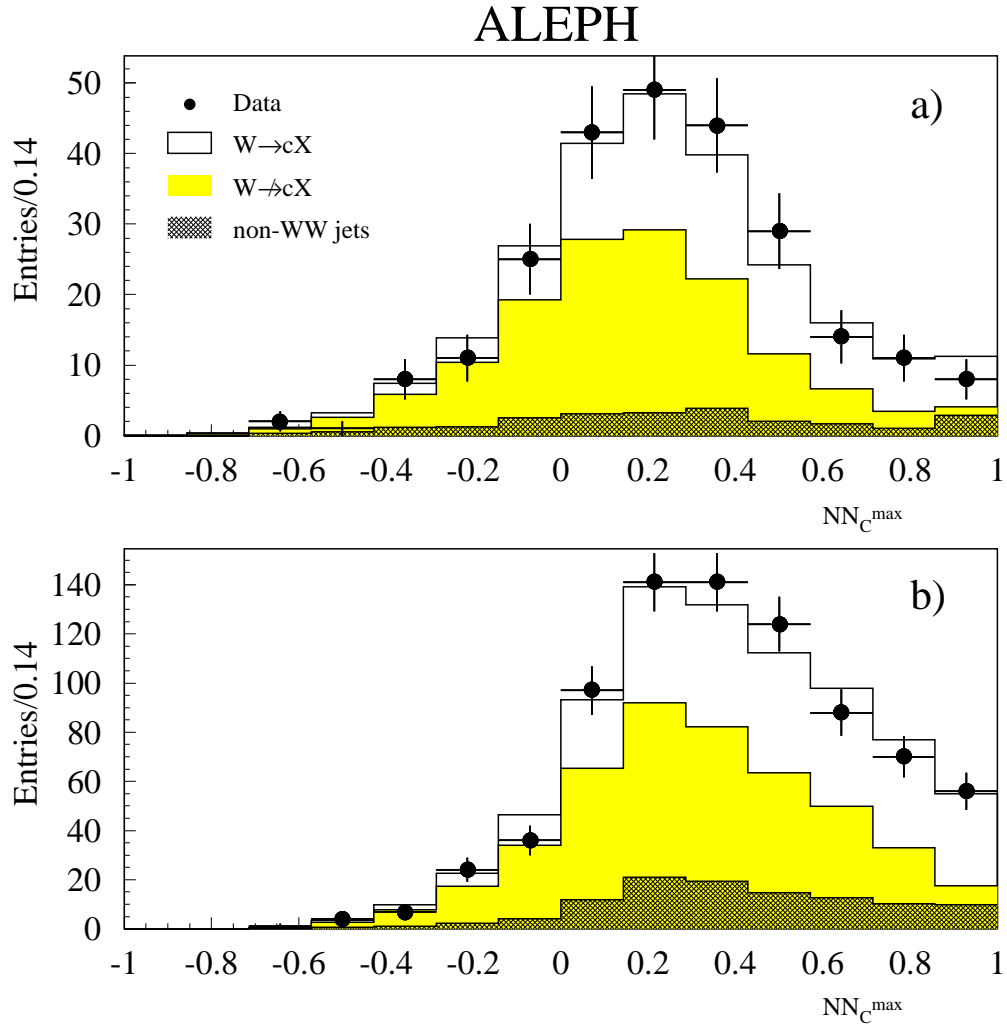


Figure 4: NN_C^{\max} output for the jet in the pair with the highest neural network output in a) $\ell\nu q\bar{q}'$ events and b) 4q events. Comparison between data and Monte Carlo normalized to the same number of entries.

5 Result

To extract R_c^W , a binned maximum likelihood fit is performed to the shape of the output distribution of NN_c^{\max} . In each bin k of this distribution, the expected number of Monte Carlo events is defined as

$$N_k^{\text{MC}} = R_c^W N_W \text{Prob}_{W \rightarrow cX}(k) + (1 - R_c^W) N_W \text{Prob}_{W \not\rightarrow cX}(k) + N_{\text{bkg}} \text{Prob}_{\text{bkg}}(k)$$

where $\text{Prob}_{W \rightarrow cX}(k)$, $\text{Prob}_{W \not\rightarrow cX}(k)$ and $\text{Prob}_{\text{bkg}}(k)$ are the probability density functions, determined from Monte Carlo, in the bin k of the NN_c^{\max} distribution for the $W \rightarrow cX$, $W \not\rightarrow cX$ and non- WW background events, respectively. The total number N_W of selected hadronic W decays is estimated as $N_{\text{data}} - N_{\text{bkg}}$, where N_{data} and N_{bkg} are respectively the total numbers of selected data and non- WW events; N_{bkg} is estimated from Monte Carlo.

Setting R_c^W as free parameter in the fit, the result is $R_c^W = 0.57 \pm 0.18$ for the 172 GeV data and $R_c^W = 0.508 \pm 0.056$ for the 183 GeV data. The linearity of the fitted value of R_c^W with the true input value is studied by generating seven different values of R_c^W ranging from 20% to 80% in Monte Carlo samples treated as “data” and by fitting these samples with a reference Monte Carlo sample corresponding to $R_c^W = 0.50$. The relationship between the fitted value of R_c^W and the true value is found to be linear with a slope consistent with unity within a precision of 4% and no significant offset observed.

The expected statistical errors have been estimated as a check using a large number of Monte Carlo subsamples of the size of the data, and taking the mean value of the fit error distributions of these Monte Carlo subsamples for the expected errors. These are ± 0.16 and ± 0.056 for the 172 GeV and 183 GeV data, respectively, in agreement with the fit errors. Furthermore, the pulls of the fitted R_c^W values have RMS and means compatible with 1 and 0. Using the fit errors, the combined result is

$$R_c^W = 0.515 \pm 0.053.$$

The values obtained for the semileptonic and fully hadronic channels are 0.537 ± 0.104 and 0.505 ± 0.063 , respectively.

From the world average values $|V_{ud}| = 0.9736 \pm 0.0010$, $|V_{us}| = 0.2205 \pm 0.0018$, $|V_{ub}| = 0.0033 \pm 0.0008$, $|V_{cd}| = 0.224 \pm 0.016$ and $|V_{cb}| = 0.041 \pm 0.003$ [1], the value of $|V_{cs}|$ derived from the measurement of R_c^W is $1.13_{-0.33}^{+0.50}$ with the 172 GeV data and $0.99_{-0.11}^{+0.12}$ with the 183 GeV data, leading to the result

$$|V_{cs}| = 1.00 \pm 0.11.$$

The values obtained for the semileptonic and hadronic channels are 1.05 ± 0.24 and 0.98 ± 0.13 , respectively.

6 Studies of systematic uncertainties

The following sources of systematic errors are considered:

1. An uncertainty of 5% is applied to the normalization of the $q\bar{q}(\gamma)$ background as estimated in Ref. [22].

2. The error resulting from the particular choice of QCD Monte Carlo generator is estimated by replacing JETSET by HERWIG for both the $q\bar{q}(\gamma)$ background and the $W \rightarrow q\bar{q}$ decays, and the full difference between the two results is taken as the systematic error. Since HERWIG is known to provide a very approximate representation of exclusive properties of hadronisation, this estimate is very conservative.
3. The effect of color reconnection is estimated by using three samples of fully simulated HERWIG WW events generated with the P_{RECO} parameter, defining the level of reconnection probability, set to 0%, 11% and 60%, respectively [23]. The largest shift obtained relative to the 0% connected sample is taken as the systematic error.
4. Effects of possible calorimeter miscalibration are studied by varying the response of the electromagnetic and hadronic calorimeters by 0.9% and 2% respectively.
5. Standard track momentum corrections are applied to all tracks in WW events; the systematic error is assessed by comparing the result of the fit obtained with and without the corrections.
6. The distribution of the track impact parameter significance in Monte Carlo events was corrected by means of the procedure described in [4], so that data and Monte Carlo have the same resolution. The associated systematic error is estimated by taking the difference of the R_c^W values obtained with and without this correction.
7. The mass of the W boson in the Monte Carlo is varied by $\pm 90 \text{ MeV}/c^2$.
8. The JADE [24] algorithm is used to form the jets instead of DURHAM-P.
9. Since this analysis is based on the properties of the decay products of the charmed hadrons, the effects related to charm production (relative production rates of the D^0 , D^+ , D_s^+ , and Λ_c), charm fragmentation and charm decay properties (D meson topological branching ratios, inclusive production of K^0 , \bar{K}^0 , K^\pm , and π^0) are studied in detail following the recommendations of [14].

The different sources of systematic uncertainties and the corresponding relative errors are summarized in Table 2.

7 Checks of the analysis

The consistency of the NN_c^{max} distribution in data and Monte Carlo is tested by means of a Kolmogorov test. This gives a consistency confidence level of 98.1% if the fitted value of R_c^W is used in the simulation, while this confidence level becomes smaller than 1% if R_c^W is set to zero.

The number of fully reconstructed D mesons in the most charm-like jet of a pair is 21 in the data; 22.6 are expected in the simulation using the fitted value of R_c^W , while only 9.8 would be expected without $W \rightarrow cX$ transitions. The number of energetic lepton candidates observed in the data is 122, while 108.5 (72.1) are expected in the simulation with (without) $W \rightarrow cX$ transitions.

Table 2: Systematic errors on R_c^W .

Source	$\Delta R_c^W (10^{-2})$
Background normalization	0.2
Hadronization	2.9
Color reconnection	0.3
Calorimeter calibration	0.9
Tracking error	0.3
Impact parameter resolution	0.4
Mass of the W boson	0.4
Jet algorithm	0.4
Charm production	0.1
Charm fragmentation	0.3
Charm decay properties	0.9
Total Error	3.3

Figure 5 shows the variation of R_c^W as a function of a cut on the output of NN_c^{\max} . Its value is seen to be stable within the variation allowed by the uncorrelated statistical errors.

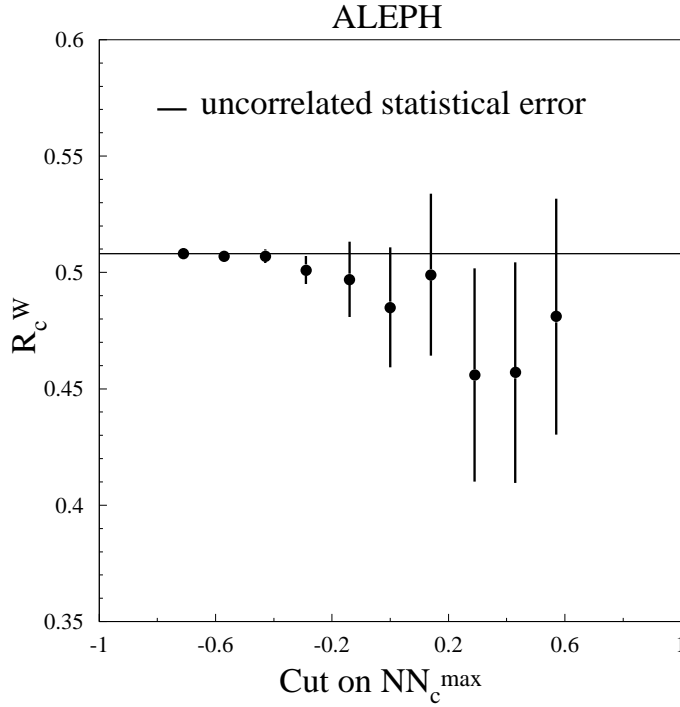


Figure 5: Values of the branching ratio R_c^W obtained at 183 GeV for different cuts on NN_c^{\max} . The uncorrelated statistical errors are calculated with respect to a cut at -0.6 , and the solid line shows the fitted value of R_c^W .

Finally, an alternative approach was developed as a check of the previous method. It is based on a Fisher Discriminant Analysis (FDA) [25] using dijets to tag the $W \rightarrow cX$ final

state. For this analysis, 12 variables closely related to those used in the neural net analysis were chosen to perform the discrimination. Each of these variables is calculated for each jet of a hadronic W decay, giving two values. The most charm-like value is then chosen and used as input to the FDA to form a single variable Y_c . This corresponds to a tag of $W \rightarrow cX$ decays and is different from the procedure used in the previous analysis which chooses between the two jets of a pair at the level of the NN_c output. Figure 6 displays the FDA output for the hadronic W decays in the semileptonic and the hadronic WW events. The output distribution of Y_c is fitted in the same way as in Section 5

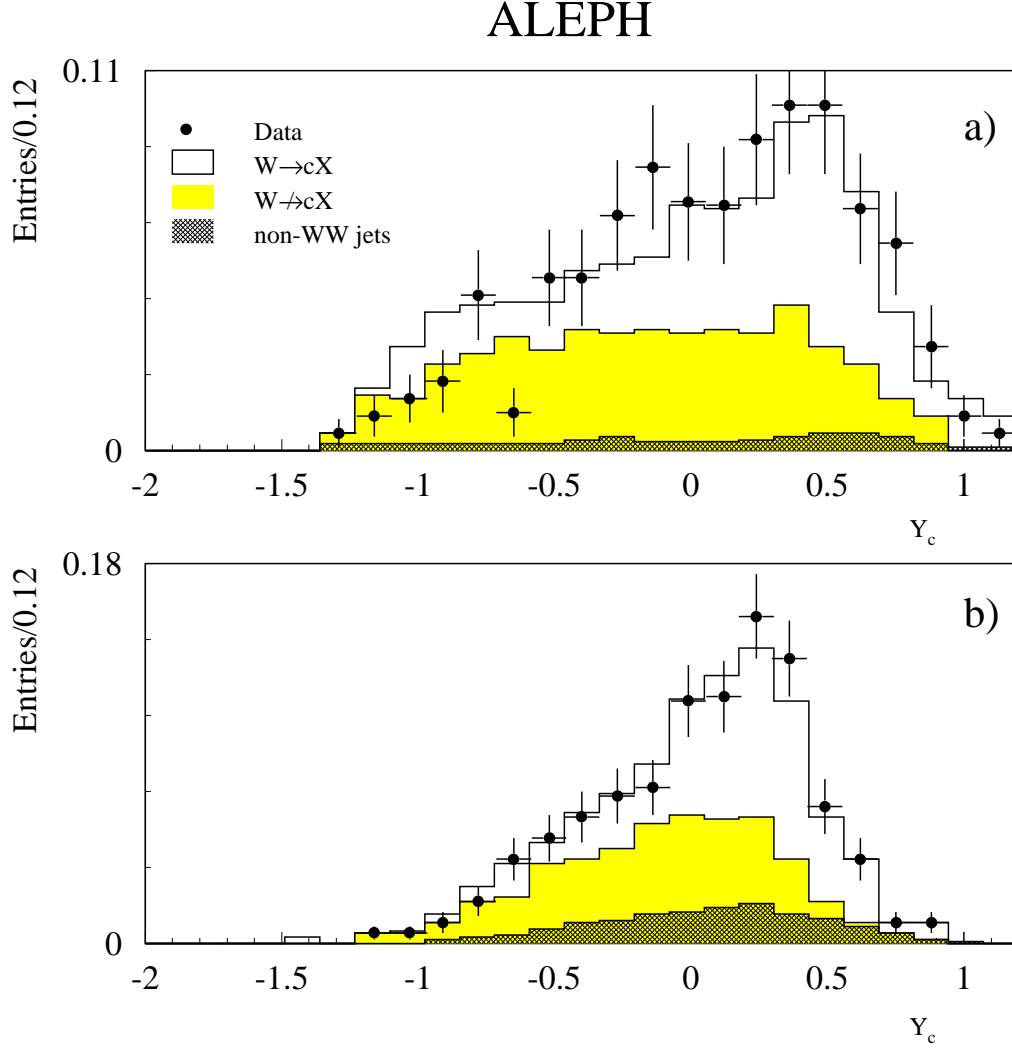


Figure 6: Distribution of the FDA output Y_c for a) $W^+W^- \rightarrow \ell \nu q \bar{q}$ and b) $W^+W^- \rightarrow 4q$ events. Comparison between data and Monte Carlo.

to get a measurement of R_c^W and $|V_{cs}|$. The result of the fit, $R_c^W = 0.503 \pm 0.065$ and $|V_{cs}| = 0.973 \pm 0.138$, is in agreement with that from the neural network analysis, with a larger statistical uncertainty.

8 Conclusion

Using a charm tag based on the properties of jets produced in W decays, the inclusive charm production rate in W decays, R_c^W , is measured. The analysis of the 172–183 GeV data collected by ALEPH in 1996 and 1997 leads to the value

$$R_c^W = \Gamma(W \rightarrow cX)/\Gamma(W \rightarrow \text{hadrons}) = 0.51 \pm 0.05_{\text{stat}} \pm 0.03_{\text{syst}},$$

from which the value

$$|V_{cs}| = 1.00 \pm 0.11_{\text{stat}} \pm 0.07_{\text{syst}}$$

is derived. The measured value of R_c^W is in agreement with the Standard Model expectation of 0.5 assuming the unitarity of the CKM matrix and with the result obtained by the DELPHI collaboration [26].

This result can be combined with the indirect measurement, $|V_{cs}| = 1.043 \pm 0.058_{\text{stat}} \pm 0.026_{\text{syst}}$, obtained from the hadronic branching ratio measurement at 161, 172 and 183 GeV [27]. The statistical errors of the two analyses are assumed to be uncorrelated and the common systematic errors are taken to be fully correlated. The weights of the direct and indirect measurements in this average are 21% and 79%, respectively. This leads to the result

$$|V_{cs}|(\text{combined}) = 1.034 \pm 0.051_{\text{stat}} \pm 0.029_{\text{syst}}.$$

Acknowledgment

We are indebted to our colleagues of the accelerator divisions for the outstanding performance of the LEP accelerator. Thanks are also due to the many engineering and technical personnel at CERN and at the home institutes for their contributions toward the success of ALEPH. Those of us not from member states wish to thank CERN for its hospitality.

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